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Land use changes and relations among water physicochemistry and hydrology in the Amazonian Purus river basin, northwestern Brazil

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Abstract

The Purus river basin is classified into the basin group that still is in a relatively high conservation status in the Brazilian Amazonian region. In areas with little degradation, the water quality is mainly influenced by natural hydrological conditions. This paper aims to quantify the Purus river basin's land cover changes over a 11-year period, and to investigate the relationships among water quality and river discharge, river level, and pluvial precipitation over a 9-year period. The hydrological and water quality variables were recorded at four monitoring stations in the municipal districts of Boca do Acre, Pauini, Lábrea and Beruri (state of Amazonas, Brazil). They were estimated a 54.4% and 36.5% increase of deforested and urban areas, respectively. Correlation analysis revealed significant relationships of the river discharge and level with the water quality variables, excepting for pH-value and dissolved oxygen. The pluvial precipitation correlated with the water quality variables mainly in the basin's most upstream areas. This preliminary analysis will contribute to gain an understanding on the interactions of the different parameters that, synergistically, determine challenges and implications for integrated land and water resources management.

Keywords: Land cover change, pluvial precipitation, Purus river basin, river discharge and level, water quality

Mudanças no uso da terra e relações entre a físico-química da água e a hidrologia na bacia do Rio Purus (Amazônia Brasileira), noroeste do Brasil. A bacia do rio Purus é classificada no grupo de bacias que ainda se encontra em um estado de conservação relativamente alto na região amazônica brasileira. Em áreas com pouca degradação, a qualidade da água é influenciada principalmente pelas condições hidrológicas naturais. Este trabalho tem como objetivo quantificar as mudanças na cobertura da bacia do rio Purus durante um período de 11 anos, e investigar as relações entre a qualidade da água e a vazão do rio, nível do rio e precipitação pluvial ao longo de um período de 9 anos. As variáveis hidrológicas e de qualidade da água foram registradas em quatro estações de monitoramento nos municípios de Boca do Acre, Pauini, Lábrea e Beruri (estado do Amazonas, Brasil). Estimou-se um aumento de 54,4% e 36,5% nas áreas desmatadas e áreas urbanas, respectivamente. A análise revelou relações significativas entre a vazão e o nível do rio com as variáveis de qualidade da água, com exceção do pH e do oxigênio dissolvido. A precipitação pluvial correlacionou-se com as variáveis de qualidade da água, principalmente nas áreas mais a montante da bacia. Esta análise preliminar contribuirá para obter uma compreensão sobre as interações dos diferentes parâmetros que, sinergicamente, determinam desafios e implicações para a gestão integrada dos recursos terrestres e hídricos.

Palavras-chaves: Mudança da cobertura do solo, precipitação pluvial, bacia do rio Purus, vazão e nível do rio, qualidade da água.

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1. Introduction

The Purus river is a whitewater river, which is turbid and have their origins in the Pre-Andean zone, from which it transports relatively large amounts of electrolyte-rich sediments. Its waters have near neutral pH and relatively high concentrations of dissolved solids indicated by the electrical conductivity that varies from 26.4 to 91.9 µS cm^{-1} (JUNK et al., 2011; RÍOS-VILLAMIZAR et al., 2011, 2014). The Purus river is considered one of the Solimões/Amazon River's main tributaries, and one of the longest rivers in South America. The estimated water discharge that is generated within the Purus river basin is about 8500 m³ s^{-1} (HAMSKI et al., 2008), and its total area is approximately 375458.46 km^2 (RÍOS-VILLAMIZAR et al., 2017). The Purus river basin is classified into the basin group that still is in a high conservation status in the Brazilian Amazon. However, the next wave of frontier expansion will take place mainly in this area that has been spared, so far, from heavy logging and deforestation due to lack of access (CARVALHO et al., 2002).

According to Souza et al., (2003), few data are available about the cumulative effects, in a hydrological microscale, of the human activities on the regional water resources, which may possibly promote changes in water distribution and quality. Water quality parameters depend on natural conditions, including hydrological factors such as river discharge, river level and pluvial precipitation, especially in areas with relatively high status of conservation (JOLLY et al., 1996; SILVA et al., 2008; HONÓRIO et al., 2010; MONTEIRO et al., 2014; OLIVEIRA JUNIOR et al., 2015). Ríos-Villamizar et al., (2017) previously diagnosed some water quality changes at the main channel of the Purus river, and related these with deforestation rates (km^2/year) and accumulated total deforestation values (km^2) of the Purus river basin. In this context, this paper aims to quantify the Purus river basin's land cover changes and investigate the relationships among river water quality, river discharge, river level and pluvial precipitation.

2. Materials and Methods

The Purus river basin is in the southwest portion of the Amazon and has the Purus river as the main tributary. It is a trans-frontier basin covering areas of the Amazonas and Acre States in Brazil, and the neighboring countries such as Peru and Bolivia. The portion located in the Amazonas State, where the water collection points are located, is covered by native primary forest and presents long areas of inundation along the meandering course of the Purus river. Although of being the main source of fish that supplies the Manaus markets, this river presents low anthropic index, with reduced areas of conversion forest in urban areas of the municipalities such as Lábrea and Boca do Acre, in the Amazonas and Acre states, respectively (SILVA et al., 2008). The Figure 1 shows the location of the Purus river and the water sampling sites.

Water samples were collected in the center of the river channel using acid-washed polyethylene bottles, which were rinsed with the water being collected and the samples were manually collected beneath the surface and kept cool until the time of the analysis. Water samples were filtered through Whatman GF/F fiberglass filters (0.7 µm). The temperature (°C) and water pH (model pH Multi 340i, WTW, Germany), electrical conductivity (µS cm^{-1}) (model cond Multi 340i, WTW, Germany), dissolved oxygen (mg L^{-1}) (model oxi Multi 340i, WTW, Germany) and Secchi disk transparency (cm) were measured in the field (on site) with standard portable devices. In the laboratory were analyzed the values of turbidity (NTU) and total suspended solids (mg L^{-1}). All the analyses were carried out by standard methods (APHA, 2005).

These data were related to hydrological variables such as average monthly river discharge and level (1998 to 2006), and monthly total pluvial precipitation (1998 to 2006). The hydrological and water quality variables as well as the pluvial precipitation data were recorded at four monitoring stations in the municipal districts of Boca do Acre, Pauini, Lábrea and Beruri in the state of Amazonas, Brazil.

The information on pluvial precipitation was reported by the Brazilian National Institute of Spatial Research (INPE), the hydrological and water quality data were obtained from four stream gauge stations managed by the Brazilian National Water Agency – ANA (HIDROWEB, 2007) inside the Purus Basin. These time series are constituted by the results of, at least, three samplings per year in each monitoring station, n = 30 (Figure 1). Spearman's rank and Pearson correlation tests were applied to identify spatial and temporal relationships. The statistical analyses were performed using Open Stat 4.0, a free code statistical program.

The determination of land use alterations over an 11-year period (1997-2007) was accomplished by using remote sensing and geographical information systems techniques. TM / Landsat - 5 sensor images with spatial resolution of 30 meters were used. The TM sensor provides data in seven spectral bands, but in this analysis only three bands (TM 3, TM 4 and TM 5) corresponding to the spectral ranges of the visible, near infrared and medium infrared, respectively, were used. The Purus river basin is covered by 25 TM / Landsat - 5 sensor scenes. A set of scenes from 1997 and 2007 were used to study the status of deforestation and the forms of land use and occupation during this period. In the digital image processing, the Spring and Envi 4.3 systems and ArcGIS 9.1 were used. The definition of land use and land cover classes was performed through the registration (or georeferencing) of the images, followed by the mosaic, segmentation of mosaic images, unsupervised and pixel-based classification. Georeferenced images were acquired from INPE.

The identification of the classes was obtained using similarity thresholds 10 and area 15. The classification of the images consisted of extracting information to recognize patterns and homogeneous objects. The unsupervised classification technique, used in this research, to classify regions of a segmented image, was the ISOSEG. This is an algorithm that groups regions from a measure of similarity between them and uses the statistical attributes of the regions, the covariance matrix and the mean vector to estimate the central value of each class (BINS et al., 1996). The measure of similarity used was the Mahalanobis distance between the class and the regions that are candidates for the relation of pertinence with this class. Finally, it was used the matrix editing tool. The edition consisted of the analysis, made by a photointerpreter, of the classes generated, using as background image the original image in colored composition (SHIMABUKURO et al., 2000). To correct the errors generated in the classification, most of the classified images were edited, eliminating or adding polygons of the classes of interest.

3. Results and Discussion

3.1. Land cover changes

Cattle ranching is considered the largest driver of deforestation in every Amazonian country, accounting for about 80% of current deforestation rates. Approximately 450000 km^2 of deforested Amazon in Brazil are being used in cattle pasture. Cattle ranching and soy cultivation are often linked as soy replaces cattle pasture, pushing farmers farther into the Amazon (MORTON et al., 2006; NEPSTAD et al., 2009, 2014; GLOBAL FOREST ATLAS, 2018). The Purus river basin is one of the most preserved basins in the Amazon region. Contrasting to other Amazonian basins, the Purus hydrological pattern probably has not been intensely modified by land use and cover change, since only about 5.4% of its area is deforested (FEARNSIDE & LAURENCE, 2002; TRANCOSO et al., 2009; DALAGNOL et al., 2017).

According to Ríos-Villamizar et al., (2017), the highest percentage of the area, in the Purus river basin, was represented by forested land (85.8%) in 2007. Nevertheless, this study revealed several land cover changes in the period of analysis (1997-2007). The most significant alteration is the increase of deforested area, which reached an estimated extent of 20610.10 km^2 in 2007 from 13347.10 km^2 in 1997 (54.4% increase) while the forests lost roughly 5966.56 km^2. Another important aspect of the identified changes is that secondary forests (forest in regeneration process) lost approximately 557 km^2 (14.2% of the initial extent). The urban areas (where the municipality seat cities are located) also presented a considerable 13.98 km^2 increase (36.5% of the initial extent). The area covered by water showed a significant 856.94 km^2 decrease (from 29070.16 km^2 in 1997 to 28213.22 km^2 in 2007). The area with presence of aquatic macrophytes was reduced approximately 40.8% from its initial extent (Table 1). As it was previously suggested by Ríos-Villamizar et al., (2017), this study also reveals that the larger deforested areas on the Purus basin are concentrated nearby the urban areas of the municipal districts of Plácido de Castro, Senador Guiomard, Rio Branco, Sena Madureira, Boca do Acre and Lábrea (Figure 2). The drainage network in this region is intersected by the Brazilian federal highway - BR 319 in several stretches, which can be considered as one of the main reasons for the large increase in deforestation before, after and in the period of analysis (MAIA, 2012; MALDONADO et al., 2012).

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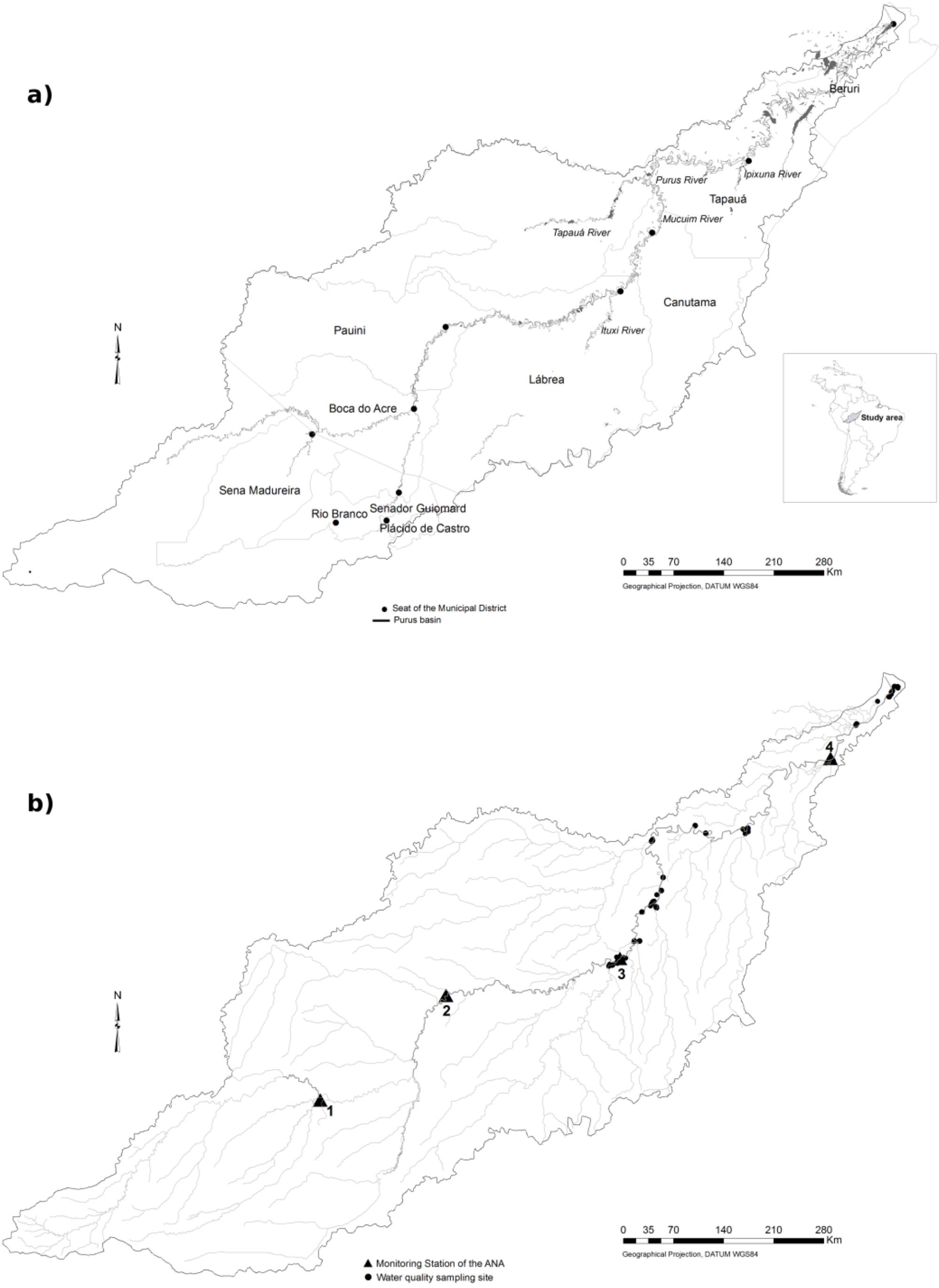

Figure 1 – The Purus river basin showing the main features and sites mentioned in the text (a), and the discharge, level and water quality monitoring stations of the ANA (b): Seringal Caridade (1), Seringal Fortaleza (2), Lábrea (3) and Arumã (4) in the municipal districts of Boca do Acre, Pauini, Lábrea and Beruri (state of Amazonas, Brazil), respectively.

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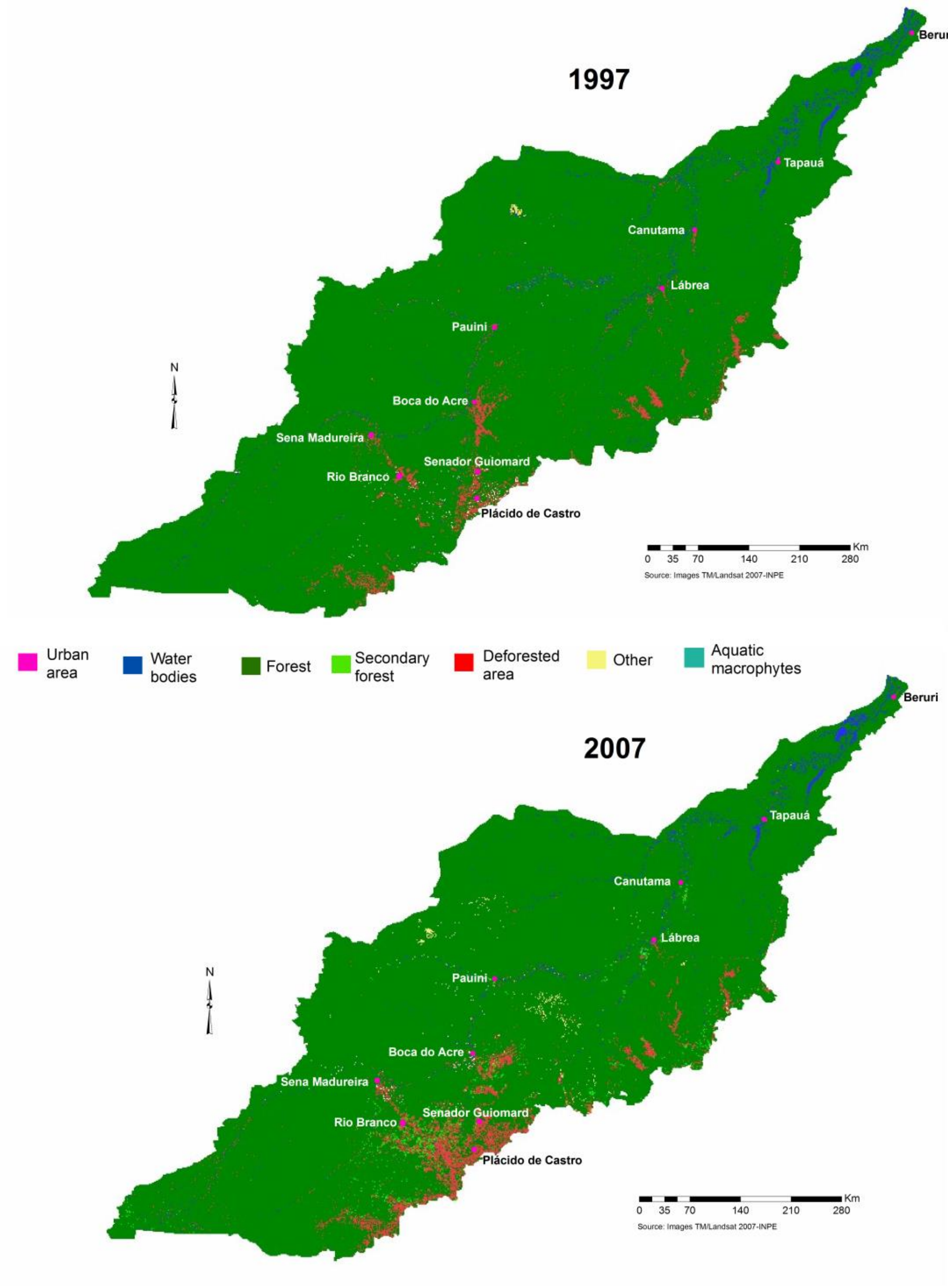

Figure 2 – Land use maps of 1997 and 2007 in the Purus River Basin (modified from RÍOS-VILLAMIZAR et al., 2017).

3.2. Hydrological variables and pluvial precipitation

In the Figure 3 is presented the annual hydrological regime of the Purus river and its interactions with the local pluvial precipitation, at the four monitoring stations, during the period 1998 to 2006. These hydrographs, of monomodal pattern, were made using historical registrations of water discharge, excepting for the station 4 (Arumã), in which was used water level data instead. Both the river discharge and river level were positively correlated ($p < 0.05$) with the total pluvial precipitation, except at the more downstream location (station 4). This may probably be related to the Purus basin response time, which is about 3-4 months (SILVA et al., 2008; DALAGNOL et al., 2017).

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Table 1 – Land use changes in the Purus River Basin between 1997 and 2007.

Land cover variables	1997		2007		Change	
	km²	%	km²	%	km²	%
Urban area	38.32	0.01	52.30	0.01	13.98	36.48
Deforested area	13347.10	3.55	20610.10	5.49	7263	54.42
Forest	328257.31	87.43	322290.75	85.84	-5966.56	-1.82
Water bodies	29070.16	7.74	28213.22	7.51	-856.94	-2.95
Aquatic macrophytes	72.33	0.02	42.78	0.01	-29.55	-40.85
Secondary forest	3923.51	1.04	3366.55	0.90	-556.97	-14.19
Other	749.73	0.20	882.76	0.23	133.03	17.74
Total area	375458.46	100.00	375458.46	100.00		

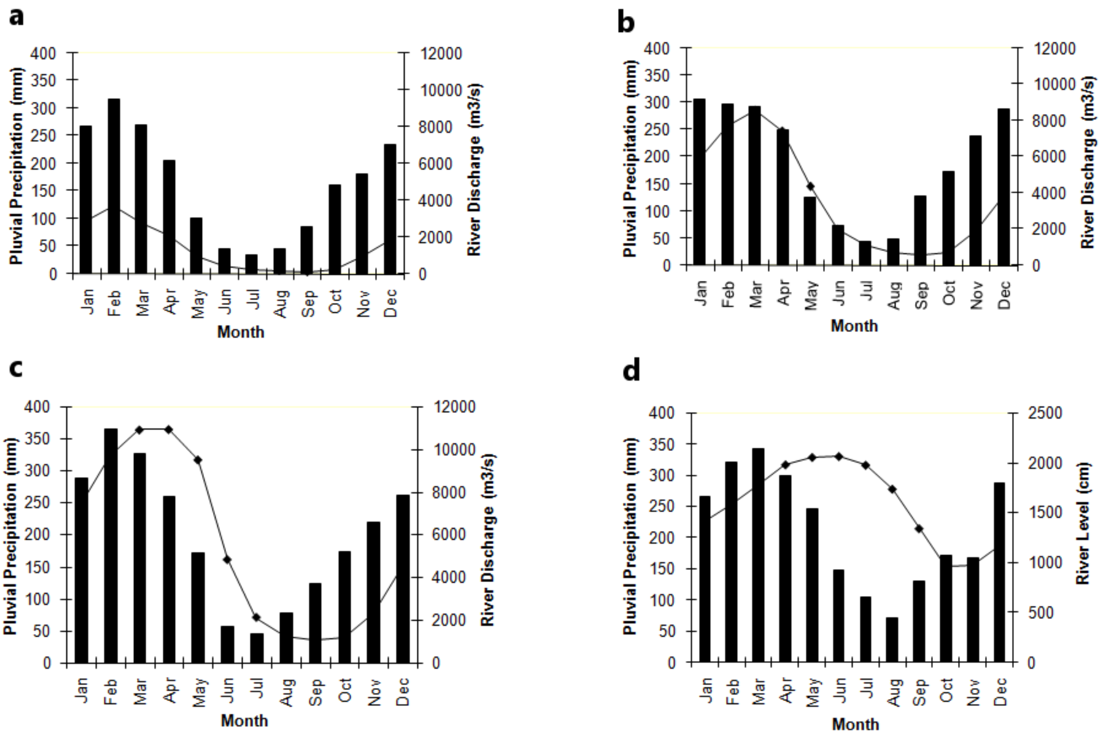

Figure 3 – Average monthly river discharge or level (solid squares) and average monthly total pluvial precipitation (bar graphs) at four monitoring stations of the ANA in the Purus River, state of Amazonas, Brazil, from 1998 to 2006: (a) station 1 – Seringal Caridade (Boca do Acre), (b) station 2 – Seringal Fortaleza (Pauini), (c) station 3 – Lábrea (Lábrea), (d) station 4 – Arumã (Beruri).

3.3. Relations among the selected water quality and hydrological variables

The pH-value did not show any relation neither with the river level nor with the river discharge, in none station. These hydrological variables showed significant negative relationship with dissolved oxygen in the station 1, TSS in the station 4 (only with river level), turbidity in the stations 1, 2 and 3, electrical conductivity in the stations 2 and 3, and temperature in the stations 1, 2, 3 and 4 (only with river level). Nevertheless, the correlation analysis revealed significant positive relationship with TSS in the stations 1, 2 and 3, turbidity in the station 4 (only with river level), and electrical conductivity in the station 1 (Table 2). The relationships displayed by the water temperature may be associated to the air temperature decrease during the wet season, in which the larger river discharges are observed (WELCOME, 1992). The contribution of ions and nutrients from agricultural areas (ARCOVA, 1996) and the "solution" effect, by means of what the salts

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contained in the dry land, which were produced by the dead vegetation, animal excrements, and ashes of burned plants, enter into the water during the flood period (WELCOME, 1992), could explain the pattern observed in the station 1 regarding electrical conductivity and dissolved oxygen. The relationships obtained in the stations 2 and 3 for electrical conductivity already were observed for the Amazon, Oshun, Ogun, Kafue, Senegal and Zambeze rivers (WELCOME, 1992). The "dilution" effect, through which the concentrations of the different water constituents decrease during the flood period (KUNKLE, 1974), is probably contributing to the relationships observed for turbidity and TSS. The results obtained for dissolved oxygen contrast with the data recorded by Bosch et al., (2002) and Mason et al., (2007). The relationships obtained for the station 4, in the Purus river's lower course, seem to reflect not only the Purus river hydrology but also the influence of the Solimões river flood pulse (JUNK, 1999; FILIZOLA et al., 2002).

Table 2 – Matrix of correlation between the hydrological and water quality variables from Purus River Basin, state of Amazonas, Brazil.

	Lev 1	Disch 1	Lev 2	Disch 2	Lev 3	Disch 3	Lev 4	Disch 4
Temp1	-0.571*	-0.569*						
pH 1	-0.038	-0.040						
E.C 1	0.559*	0.559*						
Turb 1	-0.780*	-0.825*						
D.O 1	-0.539*	-0.538*						
TSS 1	0.912*	0.906*						
Temp 2			-0.395*	-0.389*				
pH 2			-0.048	-0.052				
E.C 2			-0.429*	-0.435*				
Turb 2			-0.539*	-0.536*				
D.O 2			-0.133	-0.149				
TSS 2			0.806*	0.806*				
Temp 3					-0.716*	-0.719*		
pH 3					-0.270	-0.283		
E.C 3					-0.461*	-0.461*		
Turb 3					-0.432*	-0.438*		
D.O 3					0.087	0.087		
TSS 3					0.644*	0.635*		
Temp 4							-0.377*	-
pH 4							-0.134	-
E.C 4							-0.230	-
Turb 4							0.690*	-
D.O 4							-0.206	-
TSS 4							-0.691*	-

Note: - = not calculated; * = Significant correlations ($p < 0.05$); 1 = Station 1; 2 = Station 2; 3 = Station 3; 4 = Station 4; Temp = Temperature (°C); E.C = Electrical conductivity (μS cm^{-1}); Turb = Turbidity (NTU); D.O = Dissolved oxygen (mg L^{-1}); TSS = Total suspended solids (mg L^{-1}); Lev = Average monthly river level (cm); Disch = Average monthly river discharge ($m^3 s^{-1}$).

3.4. Relations between water quality variables and pluvial precipitation

The pH-value did not show any relationships with the monthly total pluvial precipitation, in none station. This climatic variable showed significant negative relationships with temperature in the stations 1, 3 and 4, electrical conductivity in the station 3, turbidity in the stations 1 and 2, and dissolved oxygen in the station 1. On the other hand, it displayed significant positive relationships with electrical conductivity in the station 1, and with the TSS in the stations 1, 2 and 3. The monthly total pluvial precipitation was related with the water quality variables mainly in the more upstream station (station 1) (Table 3). These results could be explained by the large river discharges in the downstream stations, which may contribute to annul the effects of the local pluvial precipitation on water quality (KUNKLE, 1974). Because of the low stream orders and minor size of drained area (HYNES, 1970), there is a close relation between the responses of the basin's upstream areas to changes in precipitation and the rainfall seasonality (WELCOME, 1992). These results could also be associated to deforestation in the area. The effects of the pluvial precipitation on water quality variables can possibly be triggered by the deforestation levels in the station 1, which are larger than the levels of the stations 2 and 4 (WAICHMAN et al., 2003; RÍOS-VILLAMIZAR et al., 2017).

Table 3 – Matrix of correlation between pluvial precipitation and water quality variables from Purus River Basin, state of Amazonas, Brazil.

	M. P. P 1	M. P. P 2	M. P. P 3	M. P. P 4
Temp 1	-0.386*			
pH 1	-0.089			
E.C 1	0.559*			
Turb 1	-0.738*			
D.O 1	-0.465*			
TSS 1	0.779*			
Temp 2		-0.092		
pH 2		-0.254		
E.C 2		-0.218		
Turb 2		-0.610*		
D.O 2		-0.103		
TSS 2		0.663*		
Temp 3			-0.402*	
pH 3			-0.049	
E.C 3			-0.381*	
Turb 3			-0.274	
D.O 3			-0.178	
TSS 3			0.425*	
Temp 4				-0.522*
pH 4				0.015
E.C 4				0.085
Turb 4				-0.186
D.O 4				0.054
TSS 4				0.145

Note: * = Significant correlations ($p < 0.05$); 1 = Station 1; 2 = Station 2; 3 = Station 3; 4 = Station 4; Temp = Temperature (°C); E.C = Electrical conductivity (µS cm^{-1}); Turb = Turbidity (NTU); D.O = Dissolved oxygen (mg L^{-1}); TSS = Total suspended solids (mg L^{-1}); M. P. P = Monthly total pluvial precipitation (mm).

4. Conclusion

The most significant estimated land cover alteration is the increase of deforested areas that have reached an extent of 20610.10 km^2 in 2007 from 13347.10 km^2 in 1997 (54.4% increase of the initial extent) while the forests and secondary forests lost roughly 5966.56 km^2 and 557 km^2, respectively. The correlation analysis revealed significant relationships among the selected water quality variables and the hydrological factors such as river discharge, river level, and pluvial precipitation, excepting for the pH-value and dissolved oxygen. The pH-value, in its turn, presented significant negative relationships with the accumulated total deforestation (ATD) in all the study sites (RÍOS-VILLAMIZAR et al., 2017), indicating that increase in the ATD may contribute to decrease the water pH-value. The dissolved oxygen presented significant negative relationships with pluvial precipitation, river discharge and river level, only at station 1. The pluvial precipitation correlated with the water quality especially in the basin's most upstream areas, and in relation to variables associated to the presence of ions and sediments in the water. This preliminary analysis on the land cover changes and the relations among water physicochemical and hydrological parameters in the Purus River Basin, may contribute to gain an understanding on the interactions of the different parameters that, synergistically, determine challenges and implications for integrated land and water resources management.

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